

Assessment of Health Effects from Exposure to Power-Line Frequency Electric and Magnetic Fields



NIEHS Working Group Report

**National Institute of Environmental Health Sciences
of the National Institutes of Health**

Assessment of Health Effects from Exposure to Power-Line Frequency Electric and Magnetic Fields

Working Group Report*

*This report represents the views and expert opinions of the Working Group
which met in Brooklyn Park, Minnesota, 16-24 June 1998

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Preface

The National Institute of Environmental Health Sciences was charged by Congress to prepare and submit an evaluation of the potential human health effects from exposure to extremely low frequency electric and magnetic fields (ELF EMF). To evaluate the quality of the science and the strength of the evidence on EMF, the NIEHS organized a comprehensive review of the data which included three science symposia and a working group meeting. The goal of the Working Group meeting was to perform a critical review and evaluation of the research data on ELF EMF exposures and potential biological and/or health effects.

Scientists both within and outside of EMF research were selected as members of the Working Group representing a wide range of disciplines including, engineering, epidemiology, cellular and molecular biology, medicine, mathematics, neurobiology, pathology, physics, statistics, and toxicology. This diversity helped to ensure a cross-disciplinary discussion of the experimental findings and broad scientific perspective.

The Working Group Report presented here draws conclusions on the strength and robustness of the experimental data related to ELF EMF and its implications for human health and disease etiology. The summaries used to define the strength of the evidence in any one area have definitions which, to properly understand the report, should be read carefully (Appendix A). The Report was completed during the 16-24 June 1998 meeting in Brooklyn Park, Minnesota and the information contained within this report reflects the deliberations and discussions of the Group. Following the meeting, the Report was reviewed and edited by a science writer for clarity and put into a common format. Systeme International (SI) units are used throughout the document. Some attempt was made to check the accuracy of references and data prior to the Report being printed; however, there was only limited time for this prior to its release to the public so there are likely to be some minor technical errors within the document.

The deliberations and summarization of the scientific data regarding possible health effects from exposure to ELF EMF are critical to the NIEHS' hazard evaluation project. This document represents the first step in a risk assessment for potential health effects of ELF EMF in human populations. The final categorizations represent strength of the evidence for a hazard and do not reflect the degree of that hazard. While there is no short summary of the results, the final discussions in Chapter 5 are sufficiently short and informative to give some indication of the overall strength of this evidence. The only way a reader can be

certain they understand these decisions is to read the appropriate sections in the book.

Preparation of the Working Group Report in a nine-day period was a monumental undertaking. There was a vast literature to cover in a short period, and the members responded to this challenge with diligence and long hours. The 30 members of the Working Group contributed approximately 1200 person-hours prior to the meeting and 3000 person-hours while at the meeting. Adding to this, the contribution of NIEHS staff and contractors shows that the document represents approximately 3 person-years of effort focused on this problem in a very short period. This effort was greatly enhanced by the summaries from the three science symposia which would add another 4 person-years to this effort.

We wish to thank the members of the Working Group for their contributions to the meeting, their dedication, and their open-minded approach to preparation of the report. We greatly appreciate the efforts of the participants in the science symposia who highlighted areas of concerns and identified key research findings for the Working Group. We also wish to thank the staff and contractors of the *EMFRAPID* Program for their technical support in preparation of the report. Finally, we also wish to thank our families and friends who have shown us continuing support throughout this effort.

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Contents

PARTICIPANTS	1
1 INTRODUCTION	7
2 OCCURRENCE AND MEASUREMENT OF EXTREMELY LOW FREQUENCY ELECTROMAGNETIC FIELDS	9
2.1 What are electromagnetic fields?	9
2.2 Measurements, unit conventions, and sources.....	14
2.3 Exposure assessment.....	17
2.3.1 Instrumentation.....	17
2.3.2 Exposure metrics.....	19
2.3.3 Exposure environments.....	22
2.3.4 Exposure assessment for epidemiological studies.....	23
2.4 Occupational exposure.....	24
2.4.1 General occupational environments.....	24
2.4.2 Visual display terminal operators.....	31
2.5 Residential exposure.....	32
2.5.1 Direct measurements.....	33
2.5.2 Calculated historical fields.....	39
2.5.3 Wire codes as an exposure surrogate.....	42
2.6 Exposure in transport.....	43
2.7 Exposure in schools.....	44
2.8 Exposure from appliances.....	45
2.9 Laboratory exposure systems.....	47
2.10 Summary.....	49
3 INTERNAL DOSIMETRY.....	79
3.1 Electric field dosimetry for human exposure.....	79
3.2 Low-frequency magnetic field dosimetry.....	80
3.2.1 Magnetic fields induced in the body by external magnetic fields.....	80
3.2.2 Magnetic fields induced in the body by external magnetic fields.....	80
3.3 Scaling between different organisms, assuming that an observed effect is due to induced electric fields.....	81
3.4 Considerations for <i>in vitro</i> dosimetry.....	82
3.4.1 Electric field dosimetry.....	82
3.4.2 Magnetic field dosimetry.....	83
3.5 Summary.....	83
4 BIOLOGICAL DATA RELATING TO THE TOXICITY OF EXTREMELY LOW-FREQUENCY ELECTROMAGNETIC FIELDS.....	85
4.1 Carcinogenicity in animals.....	85
4.1.1 One- and two-year bioassays.....	86

4.1.2 Multistep carcinogenesis.....	89
4.1.2.1 Mammary Cancer.....	89
4.1.2.2 Skin tumor models.....	95
4.1.2.3 Liver cancer models.....	98
4.1.2.4 Leukemia/lymphoma model.....	98
4.1.3 Summary.....	101
4.2 Epidemiological studies of carcinogenicity in adults.....	107
4.2.1 Occupational exposure.....	108
4.2.1.1 All cancers combined.....	109
4.2.1.2 Leukemia.....	111
4.2.1.3 Brain cancer.....	117
4.2.1.4 Breast cancer.....	119
4.2.1.5 Lung cancer.....	123
4.2.1.6 Other cancers.....	124
4.2.1.7 Central nervous system cancers in the offspring of parents exposed to electromagnetic fields.....	125
4.2.1.8 Meta-analyses of brain cancer and leukemia.....	127
4.2.1.9 Summary.....	129
4.2.2 Residential exposure.....	133
4.2.2.1 All cancers.....	133
4.2.2.2 Leukemia.....	134
4.2.2.3 Breast cancer.....	140
4.2.2.4 Tumors of the central nervous system.....	143
4.2.2.5 Summary.....	144
4.3 Epidemiological studies of carcinogenicity in children.....	167
4.3.1 Effects of power lines.....	167
4.3.2 Effects of appliances.....	178
4.3.3 Meta-analyses of studies of effects of power lines.....	183
4.3.4 Summary.....	184
4.4 Non-cancer health effects in experimental animals.....	209
4.4.1 Immunological effects.....	209
4.4.1.1 Magnetic and electric fields.....	209
4.4.1.2 Magnetic fields.....	210
4.4.1.3 Magnetic fields and 7,12-dimethylbenz[<i>a</i>]anthracene.....	211
4.4.1.4 Summary.....	212
4.4.2 Hematological effects.....	216
4.4.2.1 Magnetic and electric fields.....	216
4.4.2.2 Summary.....	217
4.4.3 Effects on the nervous system.....	217
4.4.3.1 Field detection.....	217
4.4.3.2 Avoidance and aversion.....	218
4.4.3.3 Learning and performance.....	221
4.4.3.4 Neurophysiology.....	224
4.4.3.5 Electrophysiology.....	227
4.4.3.6 Summary.....	229
4.4.4 Reproductive and developmental effects.....	237

4.4.4.1 Birds	237
4.4.4.2 Mice	238
4.4.4.3 Rats	239
4.4.4.4 Hamsters	240
4.4.4.5 Summary	240
4.4.5 Effects on melatonin.....	244
4.4.5.1 Electric fields	244
4.4.5.2 Exposure to magnetic fields for < 1 h.....	245
4.4.5.3 Exposure to magnetic fields for 1–24 h.....	247
4.4.5.4 Exposure to magnetic fields for > 24 h.....	248
4.4.5.5 Exposure to electric and magnetic fields.....	251
4.4.5.6 Summary	251
4.4.6 Bone and tissue repair and adaptation	256
4.4.6.1 Clinical bone healing with pulsed electromagnetic fields.....	256
4.4.6.2 Experimental studies	260
4.4.6.3 Summary	269
4.5 Epidemiological studies of non-cancer health effects in humans.....	272
4.5.1 Occupational exposure.....	272
4.5.1.1 Reproductive effects	272
4.5.1.2 Neurodegenerative diseases	276
4.5.1.3 Suicide and depression	282
4.5.1.4 Cardiovascular disease.....	283
4.5.1.5 Summary	284
4.5.2 Environmental exposure.....	287
4.5.2.1 Pregnancy outcome	287
4.5.2.2 Neurodegenerative diseases and neurobiological disorders.....	292
4.5.2.3 Summary	292
4.6 Laboratory studies of non-cancer health effects in humans.....	301
4.6.1 Sensation and perception	302
4.6.1.1 Field perception	302
4.6.1.2 Visual effects.....	302
4.6.2 Central nervous system.....	303
4.6.2.1 Electroencephalographic spectral analysis.....	303
4.6.2.2 Event-related potential.....	305
4.6.2.3 Sleep electrophysiology.....	306
4.6.2.4 Cognition and performance	308
4.6.3 Cardiovascular system	308
4.6.3.1 Heart rate.....	308
4.6.3.2 Heart-rate variability.....	309
4.6.4 Other effects.....	311
4.6.4.1 Melatonin.....	311
4.6.4.2 Neuroendocrinology.....	313
4.6.4.3 Immune system.....	313
4.6.5 Mood disturbances.....	314
4.6.6 Electromagnetic hypersensitivity.....	314
4.6.7 Summary	316

4.7 <i>In vitro</i> and mechanistic studies.....	326
4.7.1 Genotoxicity and regulation of gene expression.....	326
4.7.1.1 Genotoxicity.....	327
4.7.1.2 Transcription.....	330
4.7.1.3 Translation and protein synthesis.....	332
4.7.1.4 Summary.....	333
4.7.2 Signal transduction and proliferation.....	334
4.7.2.1 Calcium homeostasis and flux.....	335
4.7.2.2 Receptor-mediated signaling pathways.....	337
4.7.2.3 Cell proliferation.....	338
4.7.2.4 Enzyme synthesis and activity.....	340
4.7.2.5 Apoptosis.....	341
4.7.2.6 Summary.....	342
4.7.3 Induction of cytological markers.....	342
4.7.3.1 Embryonic staging.....	343
4.7.3.2 Matrix synthesis and extracellular interactions.....	345
4.7.3.3 Cell surface markers.....	346
4.7.3.4 Matrix interactions: Adhesion, morphology, and motility.....	348
4.7.3.5 Cell–cell communication and gap junctions.....	351
4.7.3.6 Summary.....	352
4.7.4 Summary.....	354
4.8 Biophysics of interactions of ELF EMF with biological systems.....	355
4.8.1 Biologically important interactions at the molecular level.....	358
4.8.1.1 Forces and torques on ions and molecules.....	358
4.8.1.2 Perturbation of chemical reactions.....	359
4.8.1.3 Temporal averaging and time-dependent processes.....	360
4.8.2 Comparison of changes induced by EMF and competing physical processes.....	361
4.8.2.1 Comparison with the geomagnetic field.....	361
4.8.2.2 Comparison with endogenous electric fields.....	361
4.8.2.3 Comparison with thermal noise.....	362
4.8.2.4 Comparison with shot and $1/f$ noise.....	365
4.8.2.5 Magnitude of competing thermal effects.....	366
4.8.3 Proposed physical mechanisms.....	368
4.8.3.1 Effects of electric fields on cell surface structures and cell attachment.....	368
4.8.3.2 Cyclotron resonance and ion parametric resonance.....	371
4.8.3.3 Biological electron transfer.....	375
4.8.3.4 Effects on biogenic magnetite.....	376
4.8.3.5 Magnetochemistry: Effects of magnetic fields on free-radical reactions.....	377
4.8.3.6 Non-linear dynamics and application of stochastic resonance.....	380
4.8.4 Summary.....	382
5 FINAL SUMMARY AND EVALUATION.....	395
5.1 Carcinogenicity in humans.....	396

5.1.1 Evidence from epidemiological studies to support the evaluation.....	396
5.1.2 Evidence from studies of carcinogenicity in experimental animals <i>in vivo</i> to support the evaluation.....	397
5.1.3 Mechanistic and <i>in vitro</i> evidence to support the evaluation	398
5.1.4 Discussion.....	399
5.2 Non-cancer health effects.....	399
5.2.1 Non-cancer adverse health effects.....	399
5.2.2 Other biological effects.....	401
5.3 Overall evaluation.....	402
 6 REFERENCES.....	 403
 7 ABBREVIATIONS.....	 467
 8 GLOSSARY.....	 471
 APPENDIX A - IARC Monographs Programme on the Evaluation of Carcinogenic Risks To Human - Preamble	 479
 APPENDIX B - Minority Statement on Animal Carcinogenicity.....	 505

The validity of various exposure surrogates for describing exposure to EMF in office VDT users was examined by Abdollahzadeh *et al.* (Abdollahzadeh *et al.*, 1996). They compared 8-h TWA personal exposures to 30–1000 Hz magnetic fields at waist level with a variety of surrogates including: measurements of magnetic fields at 40–1000 Hz at a fixed distance from the VDTs; reported hours of VDT use; and reported distance between the VDT and the subject's waist. The results showed a weak correlation between the 8-h TWA exposure of a VDT user and the magnetic field measured 46 cm from the VDT ($R = 0.52$, $n = 67$, $p < 0.001$). They found no association between self-reported hours of VDT use or self-reported distance between waist and VDT and the average magnetic field. Moreover, individuals' average exposure to magnetic fields did not seem to be affected by other variables such as the position of the VDT on the desk, hours of desk use, and the VDT type (color vs. monochrome).

Nair and Zhang (Nair & Zhang, 1995) also examined a variety of exposure metrics for VDTs by a method based on effects function, to determine the extent to which VDTs can be distinguished from other common sources. They found that that VDT exposure may be of consequence if exposure depends on certain types of time variation of the field. Their work demonstrates that the choice of an exposure–response relationship (i.e. the effects function) can determine if a source will make a small or large contribution to the total exposure.

A study by Lindbohm *et al.* (Lindbohm *et al.*, 1992) of exposure to VDTs in connection with spontaneous abortions incorporated both measurements and exposure surrogates. They assessed the type of VDT used and the duration of use by questionnaires and employer information. ELF and VLF magnetic field measurements on a representative sample of VDT units in a laboratory provided the exposure information. A relatively high threshold of 0.4 μT (ELF) was used for VDT readings to define the low-exposure group; the high-exposure group was defined as receiving $> 0.9 \mu\text{T}$. This grouping scheme made it likely that VDTs would be a strong contributor to exposures, although validation could not be made with personal exposure readings. Electric fields were measured with an active dipole antenna which had a frequency response extending up to 10 Mhz (see Table 2.1). The electric fields 30 cm from the screen were in the range 1.8–22 V/m.

These studies point out the difficulties of conducting a study of VDT operators due to the many possible sources of exposure and the problems in defining an exposure metric that captures the unique characteristics of VDTs.

2.5 Residential exposure

The exposure assessment method known as wiring configurations or 'wire coding' developed by Wertheimer and Leeper (Wertheimer & Leeper, 1979) in a study of childhood leukemia deserves special mention because of its place in the literature on EMF. Wire coding was developed in Denver, Colorado, USA, to provide a surrogate

measure of exposure to EMF, with a relatively simple scheme for ranking possible exposures by assigning residences into wiring configuration categories. The original classification had only two categories, but this was expanded later to five categories: underground wiring, very low current configuration, ordinary low current configuration, ordinary high current configuration, and very high current configuration (VHCC) homes (Wertheimer & Leeper, 1982). The classification scheme is based on the identifying characteristics of the power lines visible from outside a home and the distance from the home to the wires. Therefore, it does not require access to the home or instruments, and it can be used to assess exposure in current and previous residences, thus largely avoiding participation bias.

Wire coding is also a historically stable metric because the type of power distribution lines outside a house do not in general change much over the years. This method is often used in retrospective studies, in which historical stability is important; however, other types of error such as misclassification of wires may be introduced. Wire coding may also introduce confounding or bias that has not been fully understood. Researchers have continued to measure residential exposures with methods such as wire coding, despite the limitations of this method and the modest association with measurements of magnetic fields taken in residences. Wire coding does not provide an estimate of exposure to electric fields within homes (Savitz, 1993).

Table 2.6 shows the distribution of wire codes from seven studies conducted in the USA over the past 15 years. The prevalence of homes with VHCC varies markedly across the studies, from 3% in Denver to 12% in Los Angeles. As some studies excluded underground wiring in homes, the proportions in the remaining categories are somewhat inflated. Table 2.7 shows measured magnetic fields with wire code categories in six studies conducted in the USA since 1982. Measures of central tendency were selected from those available in the studies. Considerable variation can be seen in the measures in each category and particularly in the highest VHCC wire code category, probably reflecting the varying ability of wire codes to capture higher exposures. Table 2.8 shows the percentage of homes in various wire code categories with measured values above a 0.2 or 0.3 μT threshold and indicates that the usefulness of wire codes for identifying high field values in homes varies widely. The proportions in categories in studies from which underground homes were excluded should be interpreted with caution since they are inflated relative to the others.

2.5.1 Direct measurements

One of the earliest residential studies in which direct magnetic field measurements were used in addition to wiring configurations was the study of childhood cancer conducted in Denver, Colorado, by Savitz *et al.* (Savitz *et al.*, 1988). The authors relied on spot measurements of the field magnitude taken inside the residence to assess potential exposure to EMF. Although the study showed an association between wire codes and

magnetic fields, it found no association between wire codes and electric fields (see Table 2.7).

DelPizzo *et al.* (Delpizzo *et al.*, 1991) tested the usefulness of spot measurements for classifying residential levels of magnetic fields. Spot measurements were compared with data collected from stationary 24-h monitors. Homes with mean 24-h magnetic fields $> 0.075 \mu\text{T}$ were classified as exposed, and those with mean levels $< 0.075 \mu\text{T}$ were classified as unexposed. They found that a single spot measurement had at least an 80% chance of classifying a house in agreement with the classification based on the 24-h mean magnetic field and concluded that a small number of readings collected manually over several points within a home can serve to characterize the magnetic field as well as stationary monitoring. DelPizzo and Salzberg (Delpizzo & Salzberg, 1992) found that averaging four or five spot measurement readings over time instead of using a single point in time measurements resulted in a dramatic improvement in the observed-to-true ratio for classifying residential fields; however, these studies were limited because the stationary 24-h measurements in the homes were used as the measure of 'true' exposure. The authors did not measure personal exposures and could not assess the effects of personal activity and use of appliances on exposure classification.

Spot measurements were the basis of a standardized protocol for measuring magnetic fields in homes for a large study of reproductive toxicity conducted in northern California (Yost *et al.*, 1992). A pilot study, which involved taking 252 spot measurements in 24 San Francisco Bay Area homes, was conducted to identify an appropriate sampling strategy. Measurements were taken in multiple locations (center, front right, front left, back right, and back left) in the kitchen, living room, and bedroom of each home, under both low-power (all electrical devices turned off/unplugged) and normal-power conditions. They found that the center normal-power spot measurement was representative of those in other locations. In addition, 79% of the variation in home spot measurements was due to differences between homes ($p < 0.00001$). The differences between rooms were also significant ($p < 0.01$). In this protocol spot measurements were taken at the front door and in the center of the kitchen, living room, and bedroom under normal-power conditions. Under that protocol, no more than 45% (and probably considerably less) of the variance would result from within homes. The authors pointed out that London *et al.* (London *et al.*, 1991), using a similar spot measurement protocol, reported that 19% of the variance was within homes.

In an earlier study, Silva *et al.* (Silva *et al.*, 1989) reported the spatial distributions of the vertical magnetic field in five types of room found in residences: living rooms, dining rooms, bedrooms, kitchens, and bathrooms. Scatter plots of the vertical field component in the various rooms showed correlation coefficients between center-of-room measurements and elsewhere within the same room that ranged from 0.64 to near 0.8. Although measurements were performed in 81 residences, they were limited because only a single field component was recorded.

The Electric Power Research Institute (EPRI) conducted a survey of 996 residences to determine the levels and sources of residential power-frequency magnetic fields (Zaffanella, 1993). The survey, often called the 'EPRI 1000 homes study', involved a random two-stage cluster sampling plan to achieve a statistically representative sample of EPRI utility customers nationwide. This unique survey, although not designed to describe individual exposures, provides a snapshot of residential fields and the results are probably reasonably representative of residential conditions. An extensive measurement protocol was used, including spot measurements inside the rooms, field recordings in the home, Wertheimer-Leeper wiring codes, measurements of field profiles from wiring outside the home, measurements of household appliances, and measurement of fields from currents in the electrical grounding system. The overall average spot magnitude of the magnetic field inside the surveyed residences was 0.09 μT . The median value for the average spot magnetic field reading was 0.06 μT and exceeded 0.29 μT in 5% of all measured residences. The survey results were corrected by reference to the sample base population representative of national residences. About 28% (95% CI = 22–34) of the homes nationwide exceeded an average interior magnetic field magnitude of 0.1 μT , about 3.3% (95% CI = 1.7–5%) exceeded 0.25 μT , and 0.3% (95% CI = 0.1–0.6) of residences exceeded 0.5 μT .

The 1000 homes study included extensive engineering investigations to identify possible determinants of residential magnetic fields. In most residences, currents in outside power lines and currents flowing in the electrical grounding system were the dominant contributors. Power lines contributed most to the background average magnitude of the magnetic field distributed over the entire residence over the course of a day. Thus, power lines were identified as a significant source of the background fields in the home environment. Currents flowing in the electrical grounding system, in contrast, produced larger variations in magnetic fields over space and time. In some cases, specific features of the electrical system in the residence could be linked to higher magnetic fields: grounding of electrical sub-panels contributed in 4.6% of residences, multiple three-way switches in 5.2% of homes, electric ceiling heat in 2% of homes, and old-style wiring (knob and tube wiring) in 7% of homes. Other more general characteristics of the homes were also associated with higher fields. For example, fields were typically higher in older residences, homes with grounding to a metallic water line, and in duplex or apartment residences. Factors found to be unrelated to interior magnetic fields were household electric energy consumption, construction materials, presence of electric heating (other than radiant ceiling heat), and the presence of children in the home.

One goal of the survey was to evaluate various measurement methods to reliably classify residences with regard to interior magnetic fields. Previous studies had involved a variety of protocols, such as 24-h recordings and spot measurements taken in several rooms, to measure magnetic fields. One comparison of considerable interest concerns the usefulness of spot magnetic field measurements to correctly identify high-field residences. The protocol of the 1000 homes survey was similar to the California protocol described above, with spot measurements taken at the center of several rooms in the home. In the 1000 homes survey, 24-h measurements were also made of both power-line fields and

grounding-system fields and they were combined to estimate median fields in the residences. The results are shown in Table 2.9. Remarkably, the median spot readings obtained with the two methods agree quite well. This shows that spot measurements could be used as a first approximation for characterizing magnetic fields in homes.

Table 2.9. Estimated median magnetic fields in the 1000 homes survey

% of homes in which values were exceeded	60 Hz magnetic field spot measurements (μT) ^a					24-h combined field from power-line and ground system (median) ^b
	Kitchen	Bedrooms	Highest	All rooms		
				Average	Median	
50	0.07	0.05	0.11	0.06	0.05	0.05
25	0.12	0.1	0.21	0.11	0.1	0.10
15	0.24	0.2	0.38	0.21	0.17	0.18
5	0.35	0.29	0.56	0.3	0.26	0.26
1	0.64	0.77	1.22	0.66	0.58	0.55

^a Data from 992 residences

^b Data from 986 residences

^c Room with highest spot reading

Kavet *et al.* (Kavet *et al.*, 1992) assessed the exposure of adults in Maine who lived either near or far from overhead transmission lines. The assessment included 24-h personal exposure measurements, spot measurements in three rooms of every residence, and a 24-h fixed location bedroom measurement. They found greater home and total exposure for subjects residing near highly loaded transmission lines than for subjects living far away from power lines. Both the room spot measurements and 24-h fixed-site bedroom measurement were correlated with home exposure ($R = 0.70$ and 0.68 , respectively). Similarly, in another residential study, Kaune *et al.* (Kaune *et al.*, 1987) found that spot and 24-h magnetic field measurements were associated, with a correlation coefficient of 0.5 .

Kaune *et al.* (Kaune *et al.*, 1994) also studied 29 children four months to eight years of age to determine whether area (spot and/or 24-h) measurements of power-frequency magnetic fields in residences and schools could be used to predict measured 24-h personal exposures. The average 24-h personal exposure observed was $0.1 \mu\text{T}$ (geometric mean). Greater variation between subjects was found for home exposure than for school exposure. The TWA spot measurements in the home were highly correlated with residential personal exposure ($R = 0.9$). On the basis of these findings, they established a protocol for measuring residential exposures to magnetic fields. This protocol, like the California protocol developed by Yost *et al.* (Yost *et al.*, 1992) calls for the following measurements: spot measurements inside the home (center of the subject's bedroom, kitchen, and one other room occupied most frequently by the subject), spot

measurements taken immediately outside the front door, and a 24-h fixed measurement in the subject's bedroom.

The repeatability of assessments of residential magnetic fields and wiring codes was examined by Dovan *et al.* (Dovan *et al.*, 1993) in a study widely known as the 'back to Denver' study. The purpose of the study was to evaluate the long-term stability of wire codes and residential spot magnetic field readings in classifying residential magnetic fields. Wiring code and magnetic field measurements obtained in Colorado homes in 1985 as part of the Savitz study were compared with measurements taken more than five years later. The wire code measurements were in agreement for 73 of 81 homes (90%), and the correlation between spot magnetic field measurements taken in 56 homes in 1985 and measurements taken in 1990 was $R = 0.7$. A diurnal trend was observed when the average home spot measurements were compared over 24 h, the highest magnetic fields being observed in the late afternoon or early evening and the lowest in the early morning.

London *et al.* (London *et al.*, 1991) investigated the relationship between childhood leukemia and measurements of EMF in homes or exposure assessed by surrogates such as wiring configurations and self-reported use of appliances in Los Angeles County, California. They recorded detailed measurements of the magnetic field in the child's bedroom over more than 24 h (164 cases and 144 controls), spot measurements of EMF (140 cases and 109 controls), and wiring configurations. The 24-h average magnetic field recorded for the controls was reported as $0.12 \pm 0.16 \mu\text{T}$ and the 90th percentile was $0.19 \pm 0.3 \mu\text{T}$. The average electric field in the bedrooms of controls was reported as $8 \pm 12 \text{ V/m}$. A gradient in the average magnetic field readings was observed for increasing wiring configuration categories: homes with underground wiring, $0.05 \mu\text{T}$, and VHCC homes, $0.12 \mu\text{T}$. The measurements were similar to those reported by Savitz in Denver, but the prevalence of VHCC homes was higher (11% of control homes in Los Angeles and 3.1% in Denver).

The correlation between magnetic fields and exposure over time was also examined by Kaune and Zaffanella (Kaune & Zaffanella, 1994). Their exposure assessment incorporated spot measurements, stationary 24-h measurements in two locations, and personal exposure measurements for 35 children living in western Massachusetts and northern California. Measurements were taken in the spring of 1990 and again in the winter of 1990–1991. They found a poor correlation between personal exposure measured at the two times ($R = 0.1$) but fair correlations between spot measurements repeated twice ($R = 0.7$) and between stationary 24-h measurements repeated twice ($R = 0.8$).

Kleinerman *et al.* (Kleinerman *et al.*, 1997) reported on assessment of exposure to magnetic fields for a nine-state residential study of childhood leukemia. Residential magnetic fields were measured in 1354 current and former homes of cases and controls in the study. The TWA magnitude of the magnetic field weighted by the length of time the subject lived in each home was the main exposure metric. The TWA for subjects was estimated by a weighted average of the 24-h bedroom reading with spot readings taken in

other rooms. They found that 24-h bedroom measurements adequately characterized the residential exposure of children and that measurements in other rooms contribute only slightly. The mean value for the TWA magnetic field in the homes was 0.11 μT , with a standard deviation of 0.11. All of the spot readings were highly correlated with the 24-h bedroom average; the rank correlations ranged from 0.83 in the bedroom to 0.66 for kitchen locations. Front-door spot measurements provided useful information when interior measurements were missing. The rank correlation of the front-door spot reading in comparison with the 24-h reading in the child's bedroom was 0.72; this improved to 0.79 when compared with the estimated TWA for the whole residence. [This study indicates that contemporary spot measurements or front-door readings are reasonably reliable predictors of other contemporary measures of residential magnetic field magnitude.]

Friedman *et al.* (Friedman *et al.*, 1996) provided the basis for the residential magnetic field survey methods reported by Kleinerman. They compared 24-h stationary measurements in a bedroom with personal exposure measurements for 64 children aged 2–14 years during a typical weekday. The information recorded in activity diaries indicated that the children spent more than 40% of the 24 h in their bedrooms and 68% of their time at home. For children under nine, the levels of exposure at home were highly correlated with total personal exposure ($R = 0.94$); the correlation was lower in older children ($R = 0.59$). The 24-h bedroom measures correlated well with personal exposure at home ($R = 0.76$) for all of the children combined. [These results indicate that 24-h bedroom measurement is a good predictor of both residential and total personal exposure, particularly for younger children.]

Zaffanella *et al.* (Zaffanella & Kalton, 1998) made a US nationwide random-sample survey of 1000 individuals to provide a more comprehensive picture of exposure to magnetic fields. This study is the first serious effort to evaluate a cross-section of exposure to magnetic fields in the general population. Although somewhat limited by the response rates and potential participation bias, the study provides valuable insight into total exposure to magnetic fields. The preliminary results of this survey were released at a symposium on engineering research into magnetic fields organized by the DOE. The subjects for the survey were recruited by telephone, and those who agreed to participate were mailed a packet with instructions, a time-activity diary, and a personal exposure meter that recorded the magnetic field resultant at a 0.5-s sampling rate. The following conclusions were drawn from the interim analysis of 853 individuals:

- The distribution of 24-h TWA exposure in the population is approximately log-normal with a geometric mean of 0.09 μT (95% CI, 0.085–0.096) and a geometric standard deviation of 2.2 (95% CI, 2.1–2.3).
- Approximately 15% (95% CI, 12–18%) of the population was estimated to have 24-h TWA exposure exceeding 0.2 μT , about 2.4% (95% CI, 1.5–3.9%) to have exposures exceeding 0.5 μT , and about 0.4% to have exposures exceeding 1.0 μT . The

last value indicates that about 1 million people in the USA have an average 24-h exposure greater than 1.0 μT .

- Some variation in 24-h exposures was found by age: the geometric mean exposure for working-age people was about 0.1 μT , and that for retirement-age people was 0.08 μT . The geometric mean exposure for school-age children was about 0.08 μT , and that for pre-school children, 0.06 μT .
- About 0.5% of the population have an estimated maximum (peak) exposure to magnetic fields of 100 μT .

2.5.2 Calculated historical fields

Feychting and Ahlbom (Feychting & Ahlbom, 1993) conducted a study of leukemia in children living near high-voltage transmission lines in Sweden. An important feature of this study was that a computer model was used to calculate magnetic fields from the transmission lines in homes around the time of diagnosis, rather than relying on contemporary measurements. Those calculations of the magnetic fields from the transmission lines that took into account distance from the home, the power-line geometry, and the current load on the line are reliable for transmission lines because of the technical characteristics of those lines and the availability of the necessary data. Information about historical current loads on the power lines was used to calculate the magnetic fields for the year closest to the time to diagnosis. The model was evaluated by comparing calculations based on contemporary transmission line currents with contemporary spot measurements of the magnetic field. The calculated fields showed good agreement with spot measurements in single-dwelling homes. For example, in the highest measurement category ($> 0.2 \mu\text{T}$), only 15% of the calculations underestimated the contemporary measurements. The calculated values showed poorer agreement with measurements in apartments; for example, in the highest measurement category ($> 0.2 \mu\text{T}$), 47% of the calculations underestimated the contemporary measurements. The overall discrepancies between calculations and spot measurements for single homes and apartments were 11% and 32%, respectively. [While information on historical load currents permitted estimations of past exposure to magnetic fields in this study, the calculated values did not capture contributions to the field from local sources. Also, the calculated values can only be as good as the quality of the load current data.] The historical currents were known to within 100 A increments, and the average historical load current was 300 A (Kaune *et al.*, 1998). [The effect of the above factors on the amount of exposure misclassification cannot be estimated from the available information.]

The Swedish study of transmission-line fields represented an important advance over previous studies that were based on distribution-line wiring configurations in that it provides a method for estimating historical fields. The calculations are based on established laws of physics and on available physical and operational data rather than on

empirical classifications, as for the Denver wiring codes. The calculation method can not be reliably applied to distribution lines because of fundamental differences in the design and operation of the lines and the lack of historical data on load for distribution lines. Consequently, only the magnetic field contribution of the transmission lines can be reliably evaluated. Feychting *et al.* (Feychting & Ahlbom, 1993) applied the magnetic field calculation method to distribution lines near an unreported number of residences where the distribution line was judged to be a potentially important source of exposure to magnetic fields. [The questionable validity of the calculated field levels near distribution lines may have contributed to some of the inconsistency between contemporary measurements and contemporary calculations discussed above.]

Feychting and Ahlbom (Feychting & Ahlbom, 1994) conducted a study of adult cancers in relation to calculated historical fields. The exposure assessment method was virtually identical to that used by the same authors in their study of childhood cancer (Feychting & Ahlbom, 1993), except that one of the dose metrics calculated was cumulative exposure during the 15 years before diagnosis.

Li *et al.* (Li *et al.*, 1997) conducted a study of adult cancers in relation to calculated historical fields in Taiwan. They considered in some detail the locations of transmission lines (five voltage categories, from 69 to 345 kV) and homes, with distance readings derived from maps. The stated distance resolution was ± 10 m. The exposure fields were calculated from formulas based on the Biot-Savart law, accounting for line height, phasing, and other factors. No adjustment was made for local distribution lines or local sources, although for apartments the assumed building height was raised to 15 m. The historical average annual load currents, distances from homes to conductors, height of conductors, current phase, and geographic resistivity were provided by the Department of Transmission and Substation Project. Data on the resolution and accuracy of the line current used for historical measurements were not provided. The model calculations were validated by comparing contemporary calculations and measurements, with mixed results: with fields partitioned into three categories < 0.1 , $0.1\text{--}0.2$, and > 0.2 μT , the comparisons showed a concordance of 0.64 between the two exposure estimates. Measurements and calculations for the category > 0.2 μT , with cut-points 0.5 and 1 μT had a concordance of 0.82. The model calculations appeared to have the best predictive value for the highest exposure categories. [The discrepancy between calculations and measurements may be due in part to a contribution of local magnetic field sources to the field, but no indication was provided that the discrepancy is due to the presence of measured fields that were too high or too low. The ± 10 -m precision of distance could have had a significant impact on calculations for residences within 20 m of the power lines but would contribute less error for points further away from the transmission line.]

Valjus *et al.* (Valjus *et al.*, 1995) conducted a detailed analysis of historical field modeling calculations for a study of cancer in Finland. They examined the uncertainty in model calculated fields from transmission lines with considerable thoroughness. For example, the error distributions of power-line and building locations, hourly measurement records of load currents, tower dimensions, variations in conductor height, phase of currents, non-

parallel lines, and unbalanced currents were considered in a Monte Carlo analysis. The estimated precision of historical load data was examined by comparison of the estimate to currents calculated from power measurements. The estimate and the calculated value were highly correlated ($R^2 \sim 0.85$). The resolution reported for distance was ± 10 m. [Despite the completeness of the analysis, it is remarkable that no measurements of the magnetic field were performed as part of a verification process for the calculations.]

Olsen *et al.* (Olsen *et al.*, 1993) calculated magnetic fields to estimate human exposure from power lines and substations for a study of cancer in Denmark. The input parameters for the calculation include distance of the dwelling from source, type of line, dates of construction and reconstruction, average current for year, and ordering phases. [The problems with this study include: only estimates of historical load currents were available, which were provided by experts experienced in the planning and operation of the Danish transmission system; there was no experimental verification of the calculations; and the geometry of substations is much more complicated than that of transmission lines, entailing greater uncertainties. The use of experts is probably not a serious flaw, since they probably had information on historical annual currents from planning surveys.]

In a follow-up analysis of their study of childhood leukemia, Feychting *et al.* (Feychting *et al.*, 1996) investigated the importance of short-term variability in the time interval of measurement and other factors in residential exposure assessment. They evaluated the validity of contemporary spot measurements and the relative importance of distance from power transmission lines, and, when estimating past exposure to magnetic fields, calculated them with a computer model. Spot measurements were taken 5–31 years after diagnosis, with a median of 16 years. Their study showed that distance was not a simple surrogate for exposure, as first suggested. The relative risks for measurements at the time of the study (contemporary annual average fields, spot calculations, and spot measurements) were all close to or below unity. Neutra and DelPizzo (Neutra & DelPizzo, 1996) noted that spot readings appeared to have poor sensitivity, specificity, and predictive value, even though historical fields were reasonably well correlated with contemporary spot readings ($R = 0.7$).

[Together, these studies suggest that it is important to account for the historical relationship between exposure and disease outcomes. Contemporary spot or daily readings may introduce enough random and systematic error to obscure or enhance a possible association with disease risk.]

Zaffanella *et al.* (Zaffanella *et al.*, 1997) studied the use of computer modeling to estimate residential exposures, which could be useful for assessing exposure when access to residences is not possible or when planning a residential development. They used the RESICALC computer program to model magnetic fields due to currents on arbitrary configurations of electric transmission lines, primary and secondary distribution lines, and ground-return currents in neighborhoods based on residential loads and impedance.

Experiments conducted at the Magnetic Field Research Facility in Lenox, Massachusetts, simulated a residential electric distribution system. The results showed that the program could accurately model magnetic fields from both supply and ground currents. In some cases, the estimated fields were sensitive to impedance values assigned to the ground network. [Computer modeling for distribution lines requires intensive effort for input data collection, such as careful mapping of power lines, residential coordinates, acquiring load, and grounding data. These input values are critical if the model is to give valid estimates of exposure; however, because these input data are not routinely available and would require special instrumentation to be installed by the electric utility, widespread use of this computer model would be difficult.]

Bowman *et al.* (Bowman *et al.*, 1997) studied magnetic fields in residences using a physically based multipole model. The model parameters were determined by nonlinear regression techniques in order to fit the 24-h magnitude of the magnetic field recorded in a child's bedroom. The predictions were better correlated with the bedroom readings ($R = 0.4$) than with Wertheimer-Leeper wire codes ($R = 0.27$). [Since this model has not been tested in other locations, its generalizability is unknown.]

2.5.3 Wire codes as an exposure surrogate

Kheifets *et al.* (Kheifets *et al.*, 1997c) examined data on wire codes and spot magnetic field measurements from seven studies to determine the distribution of wire code categories among residences in different parts of the country. The percentage of homes falling within the VHCC category varied markedly among the data sets, but all fell within the range observed between controls in the study of Savitz (~ 3%) and in the study of London (~ 12%). Of the five studies with intermediate values, all showed less than ~ 8% homes with VHCC, except for the control homes in the study of Preston-Martin (11%) which was conducted in the same city as that of London. The number of homes in the two lowest categories was markedly smaller in Los Angeles (London *et al.*, 1994; Preston-Martin *et al.*, 1996b) than in the areas with predominantly lower-category homes. The authors also examined the distribution of spot-measured magnetic fields within each of the wire code categories in four of the data sets. All showed a monotonic trend for increasing median field with increasing wire code in the ordinary low current configuration, ordinary high current configuration, and VHCC categories, but the 10–90 percentile ranges in each category overlapped widely. The range of fields measured in each wire code category were similar in the data from the 1000 homes study and the EMDEX residential data sets (measured at numerous locations throughout the country) to that in the Savitz data set but markedly larger (spanning higher values) than that in the London data set. [These findings suggest that the relationship between wire codes and spot magnetic fields are in general similar throughout the country to that observed by Savitz in Denver but markedly different in the Los Angeles area.]

Kheifets *et al.* (Kheifets *et al.*, 1997c) also reviewed the historical stability of spot measurements and concluded that they are sufficiently stable over a period of five years

to make them suitable for estimating past exposure. In another data set, they examined the usefulness of various surrogates (wire codes, stationary measurements, spot measurements, and personal exposure measurements) for estimating personal exposure measured approximately four months earlier. Contemporary two-day personal exposure measurements were the best indicator of personal exposure, and wire codes were the poorest. The percent variability in exposure explained by the surrogate was 15% for wire codes, 46% for 24-h recordings, 54% for spot readings, and 66% for personal exposures. Contemporary spot and 24-h stationary measurements were similarly effective for estimating past exposure and intermediate between contemporary personal exposure and wire codes in effectiveness. The authors concluded that the potential for exposure misclassification when using wire codes is similar to or greater than that for contemporaneously measured magnetic fields.

Tarone *et al.* (Tarone *et al.*, 1998) examined the relationship between wire code category and 24-h magnetic field measurements on a state-by-state basis over a nine-state study area. There were insufficient data from Wisconsin for its inclusion in the analysis. More mean measured fields were in the VHCC category than in other categories in six states; two states in which there was no strong trend for increasing fields with wire code (Michigan and Minnesota) were among those with the fewest VHCC homes (four and three homes, respectively). Thus, the aberrant relationship between high wire code and field is probably a result of random variation due to small numbers. [This conclusion is supported by the observation that in the other state with few VHCC homes, the highest mean field was found in those homes.]

Tarone *et al.* (Tarone *et al.*, 1998) also looked at the distribution of homes with different wire codes, the distribution of mean and median fields within wire codes, and the percentage of homes with exposure > 0.2 and $0.3 \mu\text{T}$ within a wire code category. While wire codes did not differentiate among measured values, as in the study of Savitz, they were more effective than in the London study. The effectiveness of using wire codes was comparable to or better than that for measured data in other areas examined by Kheifets *et al.* (Kheifets *et al.*, 1997c). Tarone *et al.* (Tarone *et al.*, 1998) also looked at the reliability of wire coding in a subgroup of homes where replicate wire coding was done for quality control. Inconsistent determinations were reported for 15 of the 187 homes examined (8%). Of the discrepancies, seven involved distance and only two of the inconsistencies involved VHCC homes.

2.6 Exposure in transport

Wenzl (Wenzl, 1997) studied exposure to ELF magnetic fields among rail maintenance workers near Philadelphia, Pennsylvania. The workers were exposed to 25 Hz magnetic fields from electrified rail lines in addition to 60 Hz fields from other sources. Because of the mix of frequencies expected, spot readings of the magnetic fields were taken with a Multiwave system and fast Fourier transform to analyze for the frequency components. Personal exposure monitoring was also conducted. [The instrument response was limited

to frequencies in the range 40–1000 Hz, which would not include exposure to 25 Hz.] Current flowing in the overhead catenary lines was the primary source of magnetic fields when a train was near the maintenance work site. The peak magnetic fields were 3.4–19 μT near a transformer, while the medians at five other locations were 0.7–4 μT . TWA personal exposures were estimated by combining spot measurements at occupied locations with estimates of the amount of time spent at each location; the values were 0.3–1.8 μT , depending on the location and how frequently trains passed the work site. Comparisons between the spot measurements in the 40–1000 Hz frequency range and the personal exposure readings showed reasonably good agreement. [Further characterization of personal exposures in this environment may be justified, since workers and passengers on trains may be more highly exposed and for longer times.]

Electrified mass transit systems are found in many US cities. A US Department of Transportation study (USDT, 1993) of electrified transport systems showed that the average ELF magnetic fields in passenger coaches of trains ranged from approximately 0.5 μT in diesel-powered trains to 13.4 μT in electric-powered trains operating between Washington DC and New York. The maximum fields were found to be approximately five times larger than the average fields. Magnetic fields within the passenger coaches of mass transit systems (subways, trolleys, light rail transit systems) were highly dependent on the vehicle propulsion control system. The average magnetic fields in the passenger coaches of most trolleys and subways were 0.3–0.9 μT , but one system was found to have an average field of 17.8 μT . The principal frequency of the magnetic fields in most transport systems was other than 60 Hz, and, for many systems, the principal field components were at frequencies less than 50 Hz. Consequently, personal exposure measurements with existing exposure monitors do not accurately assess exposure to ELF magnetic fields. The electric fields were small within the coaches of all transport systems tested. Electric fields from external power supply circuits did not significantly penetrate the metallic passenger compartments. The magnitude of EMF in the drivers' compartments of the transport vehicles examined was generally comparable to or lower than the average fields within the passenger coaches.

2.7 Exposure in schools

Exposure to EMF in schools has recently received more attention because of concern raised in studies indicating associations between childhood cancer and EMF in residences. Children can spend a substantial amount of time in school, and this environment accounts for most of their daily activity away from residences. Like residences, school buildings may be located near electrical utility lines that can contribute to indoor EMF. Unlike residences, however, schools may also have extensive electrical bus networks, large transformers, and other EMF-generating equipment inside the buildings, similar to large office complexes and industrial settings.

Sun *et al.* (Sun *et al.*, 1995) conducted a survey of EMF in 79 schools in Canada for the Carlton Board of Education. They found that the typical magnitude of the magnetic field

in classrooms was lower than those in many occupational settings, with a mean of 0.08 μT (Table 2.10). They also attempted to identify possible sources of EMF, such as external wiring and building attributes that contribute to EMF in classrooms. Two-story buildings produced higher fields (geometric mean, 0.08 μT) than did one-story structures (geometric mean, 0.056 μT). Wiring in the floors of classrooms was the most frequently identified local source, while electric typewriters and computers were also common. Outside wiring was a contributing source, but transmission lines were not common enough to be identified as a contributing factor. [Overall, the levels reported in the study were similar to those in many residential and office environments.]

Table 2.10. Average magnetic flux densities in schools in Canada

Type of school	No. of schools	Mean (μT)	GM	GSD	% > 0.2 μT ^a	95% CI for GM
Elementary	57	0.085 ^b	0.065 ^b	2.0	8.1	0.054–0.078
Intermediate	7	0.072	0.061	1.9	8.3	0.037–0.099
Secondary	15	0.084	0.072	1.8	7.3	0.054–0.096
All	79	0.082 ^b	0.066	1.9	7.8	0.057–0.077

GM, geometric mean; GSD, geometric mean standard deviation

^a Percent of all readings greater than 0.2 μT

^b Summary value calculated from data in the text

The California Public Health Foundation is performing a statewide measurement survey of EMF in California schools in order to determine the range of EMF in California public schools. Measurements are to be made in a random sampling of about 90 public schools to identify and characterize the sources of the magnetic fields and to evaluate possible mitigation techniques. The measurements will include a survey of classrooms and outdoor activity areas, identification and characterization of magnetic field sources, 24-h field recordings, wire code classification, and identification of nearby outdoor electrical facilities. Preliminary results from the pilot study were presented at the 1996 DOE EMF Contractors Review Meeting in San Antonio, Texas (Neutra *et al.*, 1996). Six schools were involved in the pilot study, and 163 classrooms were measured. Approximately 4% of the classrooms measured in the study were found to have average magnetic field magnitudes > 0.2 μT ; the median value for these classrooms was about 0.08 μT . The commonest overall source of the magnetic fields was ground currents flowing on water pipes or electrical conduits, although for classrooms with fields > 0.2 μT outside distribution lines and ground currents contributed about equally to the number of sources observed.

2.8 Exposure from appliances

To date, there have been no extensive studies of the relationship between use of appliances and personal exposures to EMF. The sampling strategies must be refined in order to assess the contributions of appliances to total exposure to EMF. Fields in the vicinity of appliances have been quantified in most studies.

Gauger (Gauger, 1985) studied the magnetic fields from appliances as a function of distance. The levels near hand-held hair-dryers were 0.3–2 μT at 10 cm. Vacuum cleaners, microwave ovens, and small hand-held appliances were identified as projecting the highest fields and/or projecting the furthest distance; 95% of the maximum observed magnetic fields from appliances were $< 0.1 \mu\text{T}$ at a distance of 1.5 m.

Mader and Peralta (Mader & Peralta, 1992) demonstrated that the magnitude of magnetic fields drops off at a rate inversely proportional to distance cubed. They presented a method for assessing magnetic fields and a model for predicting the exposure of body extremities. Like Gauger, they found that proximity to the appliance was an important factor. They concluded that appliances do not contribute significantly to whole-body exposure although they may be a dominant source of exposure of the extremities.

Florig and Hoburg (Florig & Hoburg, 1990) modeled and measured magnetic fields from electric blankets. They estimated that the volume-average whole-body exposure for adults was 1.9–2.2 μT ; the corresponding values for an eight-year-old child were 2.6–2.7 μT . The magnetic field estimated at the mid-sagittal line 10 cm above the bed was approximately 1 μT . Wilson *et al.* (Wilson *et al.*, 1996) reported the results of a validation study of a protocol for measuring magnetic fields from electric blankets in homes. The average field over seven spots 10 cm above the bed was $0.45 \pm 0.05 \mu\text{T}$. The values obtained by Wilson *et al.* are within a factor of 2 of those reported by Florig and Hoburg. DelPizzo (Delpizzo, 1990) proposed a model for exposure to electric blankets, mattress pads, and other appliances. He suggested that cumulative exposure to magnetic fields of $> 400 \mu\text{T-h}$ per year would be necessary to add significant exposure over background levels.

In the EPRI 1000 homes study, Zaffanella (Zaffanella, 1993) examined a variety of household sources. Appliances were found to produce the highest magnetic fields near the source, but the fields typically decreased rapidly with distance. For example, 13 electric can openers had a median magnetic field magnitude of about 20 μT at 20 cm from the source, but this fell to 0.3 μT at a distance of 117 cm; microwave ovens had a median power-frequency magnetic field magnitude at 25 cm of 3.7 μT , which fell to 1 μT at 56 cm. The results for some other appliances in the survey are included in Table 2.11.

Table 2.11. Magnetic fields associated with use of appliances

Appliance	Distance = 25 cm			Distance = 56 cm		
	95th percentile	5th percentile	Median	95th percentile	5th percentile	Median
Non-ceiling fan	9.2	0.03	0.3	1.6		0.04
Can opener	32.5	1.2	21.0	3.2	0.2	2.4
Clock-radio (digital)	0.3	0.1	0.1	0.1	0.01	0.02
Clock-radio (analog)	2.5	0.3	1.5	0.4	0.1	0.2
Ceiling fan	1.6	0.03	0.3	0.3	< 0.01	0.1
Electric range	1.9	0.2	0.9	0.3	0.04	0.2
Microwave oven	6.7	1.7	3.7	1.7	0.5	1.0
Color TV	1.2	0.4	0.7	0.3	0.1	0.2
Refrigerator	0.5	0.2	0.3	0.3	0.1	0.1

2.9 Laboratory exposure systems

The operating constraints of systems designed for laboratory experiments of exposure characterization are very different from those of observational exposure measurements. In the laboratory setting, the operational goal is to provide a precise, known, consistent condition of exposure to EMF with as much control over environmental factors as possible. In recent years, laboratory systems both *in vitro* and *in vivo* have grown in sophistication and complexity.

The prototype of a laboratory apparatus for exposure to magnetic fields is a Helmholtz coil, consisting of a pair of circular coils aligned along their open center axis and separated by a distance of one radius. A pair of conductive parallel plates forming an air capacitor is frequently used for exposure to electric fields. Both of these devices produce a reasonably uniform magnetic or electric field around the geometric centerline; the magnitude of the field depends on the physical dimensions, number of turns in the coil, and current (or voltage) applied to the system. In the case of magnetic fields, calibration requires careful attention to construction details and precise control of the current flow in the coils. The uniform region in the center of a Helmholtz coil is rather small, and for large-scale experiments more complex coil designs may have advantages. Kirschvink (Kirschvink, 1992b) described several superior designs with three, four, or five coils which provide highly uniform fields over a large volume. Other exposure systems include solenoids (Merritt *et al.*, 1983; Mullins *et al.*, 1993) or a current sheet to produce uniform magnetic fields.

A common goal in EMF experimentation is to provide a matched control condition that is identical to the exposure in every way except for the desired field exposure. To attain this, a sham exposure is usually set up with an identical apparatus but some modification of the current flow pathway. One method is simply to interrupt the current flow of the Helmholtz pair or the voltage to the parallel plates. This method has the disadvantage that any heat produced by the energized coil is not reproduced in the sham condition. This is not of material concern if the coils are constructed with sufficiently large wire to produce

negligible heating. A superior system consists of bifilar windings around the coils, with a parallel pair of insulated wires (Kirschvink, 1992b). In normal operation, parallel currents in the windings yield an external magnetic field. In the sham ('bucked') condition, currents flow in anti-parallel directions, so that the magnetic fields generated by each strand cancel and yield virtually no external magnetic field. The double-wrapped sham produces the same ohmic heating and largely controls for temperature effects. Differences in vibration between the sham and exposed conditions may still occur, but these are usually controlled by careful isolation of the experimental subjects and solid construction of the coils. Identical and interchangeable sham and exposure systems facilitate the conduct of truly double-blind experimental protocols, because the same apparatus can be used for both experimental and control groups, with a simple switch to change the operating conditions.

Another problem encountered in laboratory systems is that stray fields produced by the exposure apparatus or other equipment can contribute to background exposure in the sham controls. Stuchly *et al.* (Stuchly *et al.*, 1991) devised a system consisting of a quadrupole-coil configuration with four square-wound Merritt coils to minimize stray magnetic fields from the exposure system. The system provides a uniform field within a volume occupied by 16 animal cages and produces a mean flux density of 2 mT which varies by < 10% over the cages. The flux density decreases to < 0.1 μ T at 2 m from the coils.

Sometimes, incubators, heaters, motors, and other laboratory equipment can produce large stray fields. To limit these fields, magnetic shielding boxes made of highly permeable materials such as mu-metal may be used. These boxes can reduce stray fields by more than 30-fold and also reduce DC fields. [The biological significance of removing the geomagnetic fields has not been thoroughly studied.] When used inside incubators, shield boxes can degrade temperature control, degrade gas exchange in the culture system, and degrade the field uniformity from theoretical calculated values. Coupling of the magnetic field to the shield box can produce significant mechanical forces, leading to greater vibration in the system.

Some experiments require exposure to combinations of AC and DC fields or control of the magnetic field vector (such as circular polarization) (Shigemitsu *et al.*, 1993). To achieve this, the exposure apparatus is made up of multiple coil windings or sets of orthogonal coils arranged to produce the desired vector components. Careful alignment of the coils and phasing of the currents is needed to produce the desired results (Doynov *et al.*, 1998). [DC magnetic fields are often not controlled in large exposure systems and can vary substantially.]

Another important aspect of laboratory system design is the control of external environmental factors, such as changes in temperature and humidity, light intensity, lighting spectrum, and noise or air-flow distribution inside the animal housing due to air-conditioning equipment. These environmental factors can provide subtle cues to animals or humans and may also alter cell culture conditions. These concerns have led to experimental designs in which assignment between sham and experimental conditions is

randomized or counterbalanced. Sometimes it is desirable to randomize cage assignments and periodically rotate cage positions to account for such environmental factors. Light exposure and timing must be controlled especially in experiments involving circadian changes in hormones or behavior. Light intensity, timing, and duration are frequently controlled, but the spectral distribution of the light is often overlooked (Prato *et al.*, 1997).

Careful measurement, spatial mapping, and periodic checking of exposure conditions in the laboratory are necessary for engineering documentation and quality control. Usually, a complete set of engineering measurements is collected before the experiments begin. This includes mapping of field uniformity and measurements of possible frequency harmonics in magnetic field readings. It is also important to characterize any switching transients or other anomalies arising from infrequent operating conditions that may occur during an experiment, such as the effect of opening an incubator door. In the past, there has been strong emphasis on reducing switching events that produce a high rate of change in the magnetic field.

In *in vitro* experiments with EMF, cultures are routinely exposed to a uniform external magnetic flux density. Initially, many researchers did not measure or estimate the resulting induced electric field strength or current density in the sample medium. The magnitude and spatial distribution of the induced electric field are highly dependent on the sample geometry and the relative orientation of the culture medium with respect to the magnetic field (Misakian, 1997; Misakian & Kaune, 1990). Bassen *et al.* (Bassen *et al.*, 1992) studied the electric fields induced in several of the most frequently used laboratory culture dishes and flasks under various exposure conditions. They developed a set of simple, quantitative tables to predict the induced electric fields and currents which were based on measurements and calculations of the electric field distributions in the aqueous sample volume subjected to a uniform, sinusoidal magnetic field of known strength and frequency. The electric field and current density can also be calculated numerically from relatively simple but flexible spreadsheet models (Hart, 1996).

These studies highlight the need for careful engineering design and evaluation of laboratory exposure systems, since all laboratory systems have potential strong points and weaknesses and involve engineering compromises. Researchers should understand these design elements in order to use the exposure apparatus to the best advantage. Close collaboration between engineers and laboratory scientists is necessary, and can result in clever adaptations of exposure systems to focus on a desired experimental test. Several funding agencies have made external site reviews for quality control.

2.10 Summary

Assessment of exposure to electromagnetic fields (EMF) is the subject of an extensive literature, much of it relating to exposure to power-frequency magnetic fields. In many of

the epidemiological studies of adults, personal exposure measurements were used to evaluate magnetic fields in the workplace or in residences on the basis of the time-weighted average (TWA) magnitude. Relatively few studies have addressed electric field exposures or investigated alternative metrics for exposure to magnetic fields, such as vector polarization, high frequency transients, and frequency harmonics.

Personal exposure has been estimated in the residential setting in order to study children's exposure. Kleinerman (Kleinerman *et al.*, 1997) estimated the exposure of 1633 children < 14 years of age and found that their daily mean exposure was about $0.11 \pm 0.11 \mu\text{T}$. These values are not based on direct personal monitoring but do attempt to account for total exposure.

Studies of occupational exposure have focused on electrical and utility workers; only recently have data become available on the exposure of the general population. Studies in the general population indicate that the median of the daily mean occupational exposure for adults is about $0.17 \mu\text{T}$. Zaffanella *et al.* (Zaffanella & Kalton, 1998) estimated that the distribution of 24-h TWA exposure in the general US population was log-normal, with a geometric mean of $0.09 \mu\text{T}$ and a geometric standard deviation of 2.2. Thus, about 15% of the population have 24-h exposures exceeding $0.2 \mu\text{T}$, about 2.4% are exposed to $> 0.5 \mu\text{T}$, and 0.5% to $> 1 \mu\text{T}$.

When they are practical, direct personal measurements of magnetic fields are generally the preferable method of exposure assessment. Direct measurements provide a quantitative estimate of exposure to a clearly defined field. Even direct measurements, however, may not allay substantial uncertainty about classification of the exposure, as factors such as seasonal variation, changes in work tasks, intermittent use of appliances or tools, changing current loads, and variable proximity to wiring can contribute to large day-to-day variation in measurements. The time of data collection during a day or a season can lead to systematic bias in estimates of daily or annual average exposure. Personal exposure monitors can also be intrusive, so that people may alter their usual activities because they are wearing the meter. Because of the wide variation in exposure to magnetic fields, very many measurements must be made in order to obtain reasonably precise estimates of exposure. It should also be noted that the TWA fails to reflect a large number of potentially relevant exposure parameters, such as time above thresholds, intermittency, and transients.

Many studies of EMF have been based on measurements at one point in time (spot measurements), stationary monitoring over time, or area measurements involving mapping of the spatial characteristics of fields. While offering a quantitative estimate of fields, such measures also lead to substantial uncertainty about exposure classification. These types of measurements have several disadvantages, including the fact that they ignore personal activity patterns such as mobility and use of tools or appliances; they do not reflect past exposure; and they exclude possible parameters of exposure such as specific frequency content, polarization, and static magnetic fields. These types of measure do, however, have the advantage of simplicity and can provide reasonable estimates of human exposure

when mobility is restricted to a particular room or residence. With additional equipment, stationary monitoring can be used to capture a wider range of EMF characteristics, providing a greater variety of potential exposure metrics. Contemporary spot measurements are useful for checking the validity and appropriateness of calculations for magnetic fields from power lines in some situations.

The value of contemporary spot measurements as surrogates for past exposure remains uncertain. The limited data indicate that spot measurements are reasonably well correlated ($R \approx 0.7$) with similar measurements over several years. Dovan (Dovan *et al.*, 1993) found that contemporary spot measurements taken within wire code categories remained correlated with home average readings collected five years earlier ($R \approx 0.7$ for low power). Dovan purposely oversampled high-field very high frequency and case homes from the data set of Savitz *et al.* (Savitz *et al.*, 1988), so this may overstate the predictive value of spot measurements somewhat. The relationship between spot measurements and personal exposure is less clear. Kaune and Zaffanella (Kaune & Zaffanella, 1994) found essentially no correlation over time for the personal exposure of children in residences; Koontz (Koontz *et al.*, 1992), in a study of children's exposure, found a significant correlation over a few days but not across seasons. In residences, the combination of 24-h bedroom measurements with spot measurements in several other rooms appears to be a good method for determining the contemporary TWA household exposures of children. The correlation improves as the age of the child decreases.

Assessment of exposure to EMF for studies of human health effects is difficult because direct measurements often cannot be obtained, particularly for studies of chronic diseases, as the exposure of interest may have occurred years previously, and the actual circumstances of exposure cannot be recreated. In such studies, therefore, all assessments of exposure, including direct measurements, are surrogates for the exposure of interest. The surrogates most widely used are contemporary measurements, job titles, proximity to electrical equipment, calculated historical fields, and wiring configuration coding (wire codes).

Occupational histories are often incomplete and lack sufficient detail on actual work activities for past exposures to be reconstructed. As exposures to EMF are not memorable, questionnaires are of limited value. Contemporary measurements of similar workplaces may account for all sources but may be poor surrogates for past exposures. Classification of exposure on the basis of 'electrical jobs' provides a crude but useful tool for studies of EMF. The wide variation in EMF intensity results in considerable overlap and misclassification. This classification scheme, however, includes few assumptions about the exposure metric used.

An alternative method is use of a job-exposure matrix (JEM) to obtain quantitative estimates of exposure to electric or magnetic fields. In modern occupational studies, the JEM appears to provide the most flexible, stable tool for reconstructing exposure. A JEM can be constructed for almost any desired exposure if measurements are available, although it still relies fundamentally on occupational titles to classify exposure. The

absence of complete data on exposures in a wide variety of occupations remains a limitation in studies of occupational exposure.

Many different surrogates for exposure have been used in studies of residential exposure, including wire coding, spot measurements, 24-h bedroom measurements, personal monitoring, and calculations based on physical models. All of these techniques have some limitations, and all of them result in misclassification of exposure. Measurements have the advantage that they capture all sources of exposure. Yet, as noted above, contemporary measurements may be poor predictors of past exposures. Estimates based on wiring configurations or model calculations are of historical value, but these techniques account only for external sources of EMF such as transmission and distribution power lines. These methods also result in misclassification of exposure, perhaps non-randomly, and tend to lead to underestimates of total exposure as many local sources are not taken into account.

The system of wire codes was developed by Wertheimer and Leeper (Wertheimer & Leeper, 1979) to predict residential magnetic fields from the distance and configuration of transmission and distribution lines near residences. The validity of wire codes has been questioned because the different wire code categories for contemporary measured fields overlap widely. Several studies have shown that wire codes can be used consistently to rank homes crudely according to the median magnetic field intensity. Dovan (Dovan *et al.*, 1993) showed that wire codes change little over time, but their usefulness for predicting past exposures remains an open question. The strengths of the wire code method include the following:

- A correlation exists between wire codes and median magnetic fields in residences.
- The codes are probably related to historical magnetic fields since the physical characteristics of power lines usually change little over time.
- Wire codes may indicate high magnetic fields in some cases.
- Wire codes make it possible to estimate fields in residences without subject participation.

The weaknesses of the wire code method include the following:

- The values for contemporary fields are widely dispersed around the median for each category, resulting in overlap among categories.
- The historical stability of wire codes, which are based on the physical characteristics of power lines, may not be a reliable indicator of the stability of magnetic fields.

- The relationship between wire codes and field intensities varies with different wiring practices.
- Exposure to local sources of magnetic fields in residences (i.e. electrical appliances, building wiring, and ground currents) and away from the residence (perhaps important for older occupants) are not captured.

Wire codes also are not a simple surrogate for the TWA magnetic field and may be related in a complex way to various field parameters. Little information is available on the relationship between wire codes and other candidate parameters of exposure such as frequency, polarization, and ‘transients’. Homes with VHCC may have a greater tendency for high-frequency transients. Kheifets *et al.* (Kheifets *et al.*, 1997c) examined several candidate metrics but found no clear relationship with wire codes.

In an alternative method for assessing residential exposure, physics-based calculations are used to estimate past fields. Generally, retrospective residential exposure assessment based on calculations of magnetic fields from nearby transmission lines on the basis of historical load currents should be more accurate than either wire codes or contemporaneous measurements, especially for single-family homes sufficiently close to a transmission line to ensure that the fields originated mainly from that source. In those homes, failure to account for fields from local sources should have less impact because transmission line fields dominate over most local field sources. The calculations for distribution lines are less reliable owing to the presence of ground currents and fluctuating loads; however, this method may be better than wire codes. Calculations for apartments, where local field sources might still dominate, are also uncertain. In some cases, the methods of calculation have been validated against contemporary spot measurements, and this has helped to establish the predictive value of the models in study populations.

Calculations of historical magnetic fields are most applicable when the geometry of the power-line sources is relatively simple, e.g. transmission lines, provided there are adequate data on load currents. Limited resolution in the measurement of distance to the residence can dominate the uncertainty in field estimates near the line. Close proximity to high-voltage transmission lines may also be an indication of substantial exposure to both magnetic and electric fields. The availability of high-quality data on load currents is also critical for this approach to succeed, although in some cases it may be possible to obtain reasonable estimates from informed experts. With the deregulation of utilities in the USA, it may become more difficult to obtain data on load currents because of proprietary interests. The strengths associated with modeling historical fields are the possibilities of estimating:

- TWA magnetic fields in homes that are not accessible;
- TWA past exposures over extended periods;

- short-term variations in fields from power lines (with good data on load current); and
- polarization and other metrics (with good data on load current).

Weaknesses associated with calculations of historical magnetic fields include:

- the inability to capture fields from local sources;
- the inability to capture non-residential exposures;
- difficulty in applying the method to distribution lines; and
- the limited availability of historical load current data.

Good instrumentation for measuring TWA exposures to EMF is available, but the complex field vector still cannot be measured completely with personal exposure meters. Some of the various exposure meters used in studies of EMF are designed for spot measurements or stationary monitoring. The currently available exposure meters have a very limited ability to detect frequency harmonics or transient fields and cannot be used to measure combined AC and DC fields or vector polarization. None of these aspects of exposure to EMF can be adequately assessed with present-day personal monitoring instruments. Consequently, the summary measures of exposure described in existing epidemiological studies involve many assumptions, and the existing exposure measures can be regarded as surrogates for the underlying ideal exposure metric. Thus, the available instrumentation has somewhat limited the ability of researchers to explore alternative magnetic field metrics in human population studies. Even if instrumentation can be improved, however, biologically based exposure metrics should be identified. Assessment of the highly variable, complex, ubiquitous exposures to EMF for studies of health effects thus requires considerable effort.